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RESIDUAL STRENGTH CHARACTERIZATION OF A CURVED INTEGRALLY-STIFFENED PANEL

By

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FOREWORD

This is a final report on the research work completed on the project "Two and Three Dimensional Elastic-Plastic Finite Element Analyses of Tapered Lok Fasteners and Residual Strength Analyses of Integral Stiffeners." This work was done under the subcategory "Residual Strength Characterization of a Curved Integrally Stiffened Panel" and specific attention was directed on investigation of crack branching and residual strength prediction with STAGS finite element code.

RESIDUAL STRENGTH CHARACTERIZATION OF A CURVED INTEGRALLY STIFFENED PANEL

B. R. Seshadri [#] and S. N. Tiwari [*]

SUMMARY

Over the years, Finite-element fracture simulation methodology has been very well established at NASA Langley to predict the residual strength of damaged aircraft structures. This methodology has been experimentally verified at NASA Langley for structures ranging from laboratory coupons up to full-scale built-up structural components with single and multiple-site damage cracking. The methodology uses the critical crack-tip-opening-angle (CTOA) fracture criterion to characterize the fracture behavior of the material. The CTOA fracture criterion assumes that stable crack growth occurs when the crack-tip angle reaches a constant critical value. The use of the CTOA criterion requires an elastic-plastic, finite-element analysis. The critical CTOA value is determined by simulating fracture behavior in laboratory specimens, such as a compact specimen, to obtain the angle that best fits the observed test behavior. The critical CTOA value appears to be independent of loading, crack length, and in-plane dimensions. However, it is a function of material thickness and local crack-front constraint. Modeling the local constraint requires either a three-dimensional analysis or a two-dimensional analysis with an approximation to account for the constraint effects. In recent times as the aircraft industry is leaning towards monolithic structures with the intension of reducing part count and manufacturing cost, there has been a consistent effort at NASA Langley to extend critical CTOA based numerical methodology in the analysis of integrally-stiffened panels.

In this regard, a series of fracture tests were conducted on curved aluminum-alloy integrally-stiffened panels. These curved panels were subjected to uniaxial tension and

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pressure loading. During the test, applied load-crack extension, out-of-plane displacements and local deformations around the crack tip region were measured. Compact and middle-crack tension specimens were tested to determine the critical angle (ψ_c) using three-dimensional code (ZIP3D) and the plane-strain core height (h_c) using two-dimensional code (STAGS). These values were then used in the STAGS analysis to predict the fracture behavior of the curved integrally-stiffened panels. The analyses modeled stable tearing, buckling, and crack branching at the integral stiffener using different values of critical CTOA for different material thicknesses and orientation. Comparisons were made between measured and predicted load-crack extension and local deformations around the crack tip region.

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LIST OF SYMBOLS

Unless otherwise stated, the listed symbols are specified as follows

$2a_i$	Initial crack length crack, in.
$2a_f$	Fatigue crack length crack, in.
B	Specimen thickness, in.
d	Minimum element size along crack line, in.
h_c	Plane-strain core height, in.
E	Young's modulus, ksi
K	Stress intensity factor, ksi$\sqrt{in}$.
P	Applied load, kips
S	Applied stress, ksi
W	Width of specimen, in.
X,Y,Z	Cartesian coordinates
ν	Poisson's ratio
δ_5	Crack opening displacement, in.
ψ_c	Critical crack tip opening angle, (CTOA), deg.
σ_{ys}	Yield stress, ksi
σ_u	Ultimate tensile strength, ksi

LIST OF FIGURES

INTRODUCTION

In recent times, there has been a consistent effort by the aircraft industry in exploring the prospect of replacing built-up structures with integral structures for aircraft applications. With the emergence of high speed machining and improvements in other manufacturing technologies, there is a great promise to greatly reduce part count and manufacturing cost [1,2], but methods need to be developed to predict the residual strength of these structures. As part of the NASA Airframe Structural Integrity Program [3], a fracture simulation methodology based on the critical-crack-tip-opening angle (CTOA) has been developed to predict the strength of damaged aircraft structures. The methodology has been experimentally verified for structures ranging from laboratory coupons up to full-scale built-up structural components with single-crack and multiple-site cracking [4-6]. In this direction, numerical prediction methodology based on CTOA has been developed to evaluate integral structures for the aircraft industry. The developmental work involved extensive modifications that account for crack branching into integral stiffeners and thickness variations in the panel. The developed numerical methodology was validated by predicting the residual strength of a series of flat integrally-stiffened panels that were designed and tested for residual strength at the NASA Langley Research Center [7-8]. In addition, same numerical methodology was used to predict the residual strength of flat thick integral panels that were designed and tested at the Alcoa technical center [7-8]. The developed numerical methodology predicted the residual strength of both the set of panels that were tested at NASA Langley and ALCOA [9] within three percent of the experimental maximum load [7-8]. Later on it was decided to validate the developed numerical methodology by predicting the residual strength of curved integrally stiffened panel, more representative of an aircraft fuselage section. These curved integrally stiffened panels were tested at NASA Langley and these panels were subjected to much more complex loading as experienced by an aircraft fuselage [10]. This report reviews some of the milestones accomplished in the residual strength prediction methodology for curved integrally-stiffened panels.

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EXPERIMENTS

Fracture tests on standard laboratory fracture specimens and on 48-inch wide curved integrally-stiffened panels were conducted at the NASA Langley Research Center (LaRC). The laboratory specimens and the integral panel were made of 7050 aluminum alloy material. All of the laboratory specimens were tested with anti-buckling guides. Both compact tension, C(T), and Middle cracked tension, M(T), specimens of various widths (W = 2 to 24 in) and thicknesses (B = 0.06 to 0.25 in) were tested. The specimen geometries and dimensions are shown in Figure 1. The curved integrally-stiffened panel shown in Figure 2, was machined from a 1.5-inch thick plate. Five integral stiffeners of different cross sections were located symmetrically across the width of the panel. The cross-sectional view of the curved integrally stiffened panel is show in Figure 3. As shown in the figure, the curved panel has I, inverted L and blade integrals located symmetrically across the width of the panel. The integral stiffeners were orientated in the direction of loading and perpendicular to the direction of the central offset lead crack as shown in this figure. The curved panel was subjected to a combination of pressure and tension loading. It is a much more complex loading as there is considerable bulging of the panel due to pressure loading. A very sophisticated geometric non-linear analysis is required to capture the non-linear behavior of the curved panel. The panel tested contained a 7-inch long crack centered across, and severing the middle integral as shown in Figure 2. During the tests, measurements were made of applied load, crack extension, out-of-plane displacement, stroke displacement, and strains in the crack-tip region and in the integral stiffeners. These panels were tested without anti-buckling guides.

PRELIMINARY TEST

Before carrying out fracture test, a series of preliminary tests were carried out on 48-inch wide curved integrally stiffened panels. These tests were carried out to make sure that both tensile and pressure loading is quite accurately applied on to the panel from the loading jacks. The applied tensile loading was kept to a minimum value to prevent yielding of the panel. The curved panel is fitted with stain gages at salient locations both

on sheet surface and the integrals to record the deformations. During each tensile linear loading and unloading, strains were recorded at various locations on both sheet surface and integral. The corresponding lading patterns were simulated in the STAGS numerical analysis to make sure that boundary conditions are properly applied to the finite element model. The preliminary check and comparison will make sure that load transfer is taking place quite accurately in the finite element model. Comparison of applied load against stain gage reading for one of the location on the curves sheet surface is shown in Figure 4. Open symbols correspond to test front and back strain gage readings. The corresponding STAGS analysis result is shown by lines. From the figure, the analysis results compare well with the experimental data indicating that boundary conditions are applied quire accurately to the finite element model of curved integrally stiffened panel. On similar lines, comparison of strain gage data for the integral along with the analysis results are shown in Figure 5. Once again the analysis results(lines) compare quite well with the experimental data (symbols). From both the comparison, it's quite clear that, the boundary conditions are applied properly to the finite element model and the applied load is getting transferred quite accurately in the finite element model of the curved integrally stiffened panel.

FRACTURE ANALYSES

The fracture analyses of all laboratory specimens and curved panel tested at NASA Langley were conducted using STAGS (STructural Analysis of General Shells) [11] codes with the constant critical crack-tip-opening angle (CTOA) fracture criterion [12]. STAGS is a finite element program for the analysis of general shell-type structures [11]. The program has several types of analysis capabilities (static, dynamic, buckling, crack extension, material nonlinear and geometric nonlinear behavior). STAGS has crack extension capability based on the critical crack-tip-opening angle or displacement (CTOA or CTOD) criterion, the T*-integral and the traditional K_R-curve. In the current study, quadrilateral shell elements with 6 degrees-of-freedom per node (three displacements and three rotations) were used in the model. The quadrilateral shell element was under 'plane-stress' conditions everywhere in the model except for a 'core' of elements along the crack plane that were under 'plane strain' conditions [13-14]. Elastic-plastic material

behavior of the sheet and stiffener were approximated by multi-linear stress-strain curves. The White-Besseling plasticity theory was used to account for yielding and reverse yielding [11]. The analysis methodology followed and the calibration procedure adopted in the determination of fracture parameters are discussed in the following sections.

Analysis Methodology

The analysis methodology used to characterize the critical CTOA value (ψ_c) for each material thickness was to match the maximum load from the analysis with the average maximum load for the tests. Three-dimensional finite element analyses (ZIP3D) with the small strain option (for consistency with the STAGS small strain formulation) were used to find the critical angles. By using these angles in the STAGS analyses, the plane-strain core heights were estimated. The fracture parameters that are required in the analysis are shown in Figure 6. The determination of critical angle and plane-strain core height will be discussed in the following section.

The CTOA fracture criterion assumes that stable crack growth occurs when the crack-tip angle reaches a constant critical value and requires an elastic-plastic finite-element analysis [4-6,12,15]. The critical angle appears to be independent of loading, crack length, and in-plane dimensions, if the crack length and remaining ligament are greater than approximately 4 times the sheet thickness. However, CTOA is a function of material thickness and local crack-front constraint. The critical CTOA criterion is equivalent to a critical CTOD value at a specified distance behind the crack tip [12,15].

At each load increment, the CTOA is calculated at a fixed distance behind the current crack tip and compared to a critical value (ψ_c). When the CTOA exceeds the critical value, the crack-tip node is released and the crack is advanced to the next node. This process is continued until crack growth became unstable under load control or until the desired crack length is reached under displacement control (herein, all analyses were run in displacement control). As the crack grows with stable tearing in the integral panel, the crack tip passes through sections of various thicknesses. In addition, when the lead crack approaches and severs an intact integral stiffener, crack branching occurs. A

schematic representation of crack branching is shown in Figure 7. With crack branching (Fig 7), crack growth of multiple cracks is controlled by different values of critical CTOA at each crack tip. To carry out stable tearing analysis with STAGS, the critical CTOA, which governs the onset of crack growth, and the plane-strain core height, which simulates the three-dimensional constraints around the crack-front region, needed to be determined. For this purpose, the load-crack-extension results from the C(T) and M(T) specimens that were restrained from buckling were used.

The concept of defining plane-strain elements around the crack-front region [13-14] is adopted in two-dimensional analysis to simulate three-dimensional constraint conditions around a crack front. Previous analyses of wide flat panels [4-6, 13] have shown that the high-constraint conditions around a crack front, which can be approximated as plane strain, must be modeled in order for the critical CTOA criterion to predict wide panel failure from small laboratory tests. The plane-strain core is defined as a strip of elements parallel to the crack plane with a half-height of h_c. The plane strain core height for each material thickness was determined by adjusting the core height such that the maximum load from the analysis approximately matches the maximum load from the test. In each case, the critical angle obtained from the respective three-dimensional analysis was used.

Minimum Element Size

To model the fracture process with the CTOA failure criterion, an array of small elements was positioned along the crack symmetry plane. Previous parametric and convergence studies showed that a uniform crack-tip element size of 0.04-in. (linear-strain element) was sufficient to model stable tearing under elastic-plastic conditions [4-6, 15]. Crack growth was governed by monitoring the critical CTOA (Ψ_c) at a distance of 0.04-in. (one element) behind the crack tip.

Accounting for Buckling and Crack Branching

Seshadri and Newman [4-6, 16] have demonstrated that stable tearing in the presence of buckling can be predicted with STAGS and the CTOA fracture criterion. A bifurcation

analysis was conducted to determine the first buckling mode shape. This out-of-plane displacement shape (about 10% of the sheet thickness) was then introduced as an imperfection in the model for the non-linear analysis. When the lead crack approaches the intact integral stiffener during stable tearing, the crack branches into two with the main lead crack continuing along the X-direction in the panel and the secondary crack growing along the integral stiffener. Figure 7 shows a schematic representation of crack branching. Each material thickness and orientation has a separate critical crack tip opening angle.

Determination of Critical CTOA and Plane Strain Core Height

The analysis results for the 12-inch wide, B = 0.06 inch thick M(T) specimen are compared with the experimental data in Figure 8. In this figure, open symbols show results from the three tests. The critical angle that allows the ZIP3D [17] analysis to match the average experimental maximum load is 4.85 degrees. With the same CTOA of 4.85 deg., the STAGS analysis with plane strain core height of 0.08 in. compares well with experimental and ZIP3D result.

Figures 9 and 10 show the analysis results that best matched the experimental data for the 24-inch wide LT, 0.06-inch thick M(T) specimen, and for the 12-inch wide TL, 0.12-inch thick M(T) specimens, respectively. The ZIP3D analysis results (ψ_c = 4.85 deg.) in Figure 9 for the M(T) specimens are remarkably close to the test data. Comparing figures 8 and 9, it's clear that the prediction made with same CTOA angle of 4.85 degree for both the widths compares well with the experimental data. Also, for both the widths, the STAGS analysis with the same CTOA and plane stain core height compares very well with experimental data. The results in Figure 10 for the 12-inch wide TL, M(T) specimens compare well with the experimental data. In this specimen, the crack growth is in TL direction. Due to this, there is less resistance to crack growth and the critical CTOA required to predict the experimental maximum load is also lower. ZIP3D and STAGS analysis with critical CTOA of 4.15 degrees compares well with the experimental data. For more information on laboratory test results and there interpretation please refer to References [7-8,10].

The dashed lines in Figures 8-10 show the STAGS results that best match the experimental results. In all cases, the STAGS analysis results compared very well with the test data and three-dimensional ZIP3D analyses. Once the required plane strain core heights were determined for various thicknesses, the residual strength analysis of the 48-inch wide curved integral panel was performed with the STAGS finite element code.

FRACTURE ANALYSES OF 48-INCH WIDE CURVED INTEGRALLY STIFFENED PANELS

The STAGS finite-element shell code and the critical crack-tip-opening angle (CTOA) failure criterion were used to model stable tearing of cracks and to predict residual strength behavior of the curved integral panel fracture test. Figures 2, 3 and 11 show the curved integrally stiffened panel configuration and a typical finite-element model of the panel used in the analysis. Because the configuration and loading were symmetric about the crack plane, only quarter panel was modeled. Figure 11 shows the mesh pattern of the panel. The remote loading was applied as uniform displacement and the panel was subjected to a uniform pressure. This model contained 12,729 nodes, 10,334 shell elements and 76,374 degree-of-freedom (DOF). The following sections discuss the stable crack growth analyses of the curved integrally stiffened panel. Load crack extension data, strain gage readings from the STAGS analysis are compared with the test data.

Comparison of Load-Crack Extension Results

Figure 12 show the comparison of test measurements (open symbols) and analytical prediction (solid line) for the curved panel. As mentioned before, the panel tested had 7.0 inch lead crack located centrally across the width of the panel as shown in Figure 2. The insert shows the relative location of the integral stiffener close to the crack tip. Test data corresponding to both right and left crack tip are indicated by circular and square open symbols respectively. The STAGS analysis prediction is represented by solid line. Figure 12 shows that failure occurred when the crack tip reached the edge of the integral stiffener (solid symbol). The analysis predicted similar behavior; the crack growth became unstable when the crack tip entered the integral stiffener. The STAGS analysis

very well predicted the failure load within 5% of the test failure load. Even though the STAGS analysis very well predicted the failure load, the path taken to reach the failure load during the transition region does not compare well with the test data. The reason being that analysis is not able to capture the correct out of plane deformation around the crack tip region due to pressure loading.

In order to make sure that the analysis captures the non-linear geometric out-of plane deformation around the crack tip region due to pressure loading, the element around the crack tip region was further refined by an order. Instead of having 0.04 in. elements, now the crack tip element size is 0.02 inch. The smaller size elements help to capture the non-linear out of deformation behavior. The residual strength analysis of curved integrally stiffened panel was carried out with refined mesh and the comparisons of analysis result with experimental data are shown in Figure 13. By reducing the size of the crack tip element size by an order, the analysis was able to capture the out of deformation accurately. The load-crack extension results from the analysis compares well with the experimental data. With the refined mesh, the analysis captures the load-crack extension data but there is an offset in the predicted failure load by 8% from experimental data. As mentioned before, the lead crack enters the thick integral and branches into two cracks before unstable crack growth occurs. It means that there is a crack growth of couple of millimeters in the thick region before panel failure. It needs to be accounted for in the analysis by using the correct critical CTOA and plane strain height corresponding to the thick region thickness. Earlier the same critical CTOA angle of 4.85 degree and plane strain core height of 0.08 inch was used for both thin and thick section in the comparison.

Since no C(T) or M(T) laboratory specimen corresponding to integral region thickness of B=0.17 inch was tested, an interpolation was done to get the correct critical CTOA from the available test data. The available load-crack extension data for 2-inch wide, B=0.12 inch C(T) and 12-inch wide, B=0.25 inch M(T) are shown in Figures 14 and 15. Once again open symbols correspond to test data and analysis results are represented by solid lines. The analysis results compare well with the test data.

Corresponding to thickness of, B=0.12 inch and 0.25 inch, the predicted critical CTOAs are 4.95 and 6.2 degrees respectively. With the available critical CTOAs for different thicknesses from various laboratory specimens, a plot of variation in CTOA against thickness is shown in Figure 16. From the figure, the critical CTOA corresponding to integral thick region of B=0.17 in. was interpolated to get a critical value of 5.40 degrees. Now this critical CTOA was used in the thick integral region in the residual strength prediction.

Comparison of load-crack extension data from the analysis of curved integrally stiffened panel with different CTOAs corresponding to various sections along with the experimental data is shown in Figure 17. Once again open symbols correspond to test data and STAGS analysis prediction is represented by sold line. The solid line represents the analysis prediction with different critical CTOAs corresponding to different thickness. In this prediction, CTOA of 4.85 degree was used when the crack was extending in the section of B=0.06 inch and 5.40 degree when the crack was extending in the section of B=0.17 inch. By using appropriate CTOAs corresponding to different thickness, the analysis not only captures the load-crack extension behavior but also predicts the panel failure load within 3% of test failure load. Even though the crack grew by a couple of millimeters in the thick region before failure, by using the correct fracture parameters namely CTOAs and plane strain core height corresponding to different sections, the STAGS analysis was able predict the residual strength and crack grow behavior quite accurately.

Comparison of Strain Gage Measurements

Analysis results are compared with local strain gage readings in Figures 18. The integral panel had strain gages mounted at several distinct locations on the sheet and on the stiffeners (front and back). The insert shows the location the strain gage on the integral and they were located 2-inches above the initial crack symmetric plane. The comparative results are shown in Figure 18. Open symbols correspond to left and right crack tip. Solid and dotted line correspond to analysis results. With increase in applied load, the crack tip continues to grow towards material point and there is increase in strain

as indicated by both right and left strain gages (open symbols). The analysis results represented by lines very well capture this behavior at these locations and compares well the strain gage measurements.

CONCLUSIONS

The STAGS finite-element code and the CTOA fracture criterion were used to predict stable tearing and residual strength of a curved integrally-stiffened panel made of 7050 aluminum alloy. By using critical crack tip opening angles and plane strain core heights calibrated from laboratory coupons, the residual strength of 48-inch wide curved integrally stiffened was predicted using STAGS and it was within 3% of the test failure load. The strain gage readings from the analysis compared very well with the test measurements, which indicate that, the overall load transfer and load distribution is correct. The analyses has shown that it is very important to calibrate right fracture parameters namely, critical CTOA and plane strain core height corresponding to different section of various thicknesses for accurate prediction of residual strength. Also, depending upon the type of loading, the crack tip elements need to be refined to capture the out of plane deformation accurately. With coarse tip elements, it is very difficult to capture severe out of plane deformation under pressure loading. These studies have demonstrated that both STAGS and ZIP3D have all the capability and features that are required in the analysis of both thin and thick integrally stiffened panels under complex loading conditions. These analysis codes will be enhanced as necessary in near future depending upon the requirement. With the success in the fracture analyses of cracked integrally-stiffened panels, the finite-element software and CTOA fracture criterion are be very useful in the future fracture design of integrally-stiffened thin and thick structures for aerospace industry.

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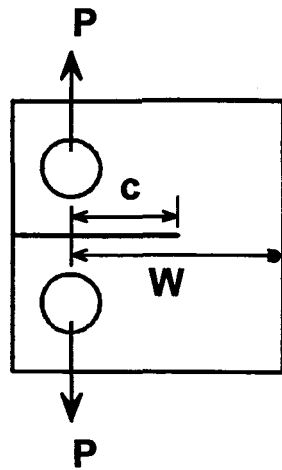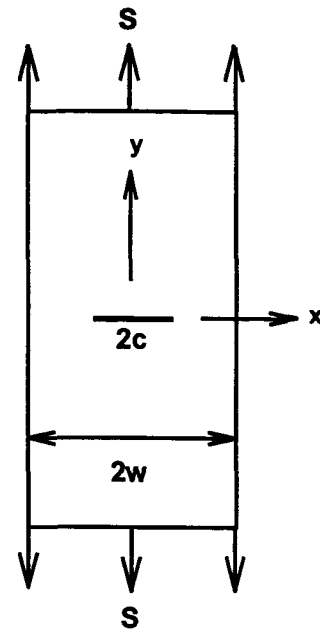
(a) Compact, C(T)   (b) Middle cracked tension, M(T)

Fig. 1. Laboratory specimens for critical Crack-Tip Opening Angle (CTOA) characterization.
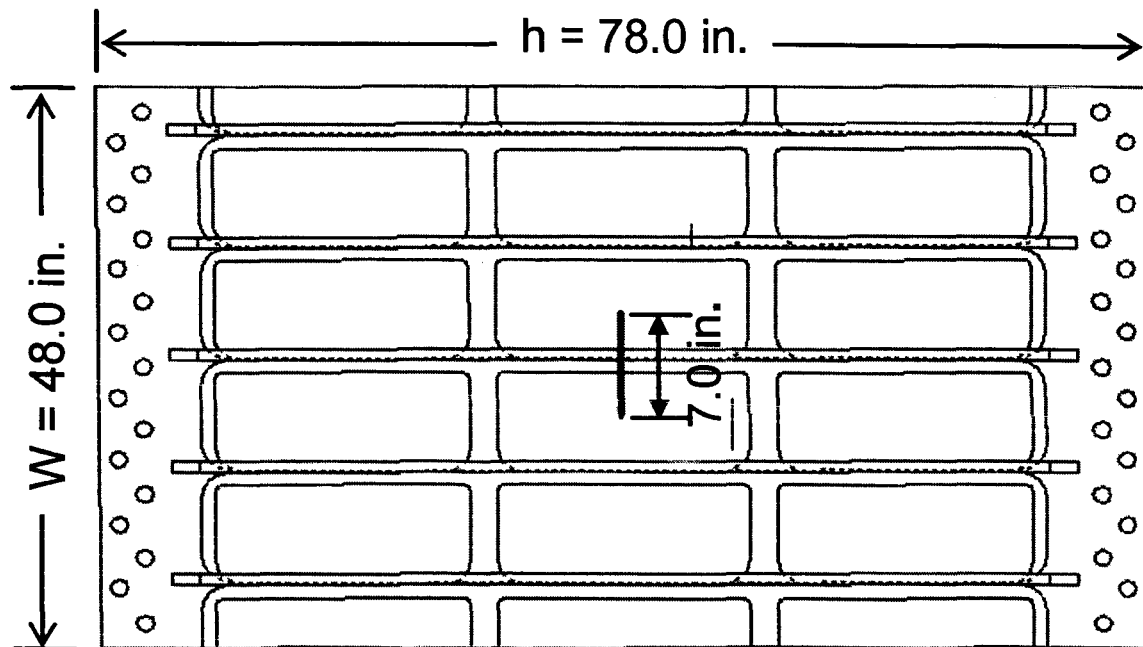
Fig. 2. A typical 48-inch wide curved integrally-stiffened panel.
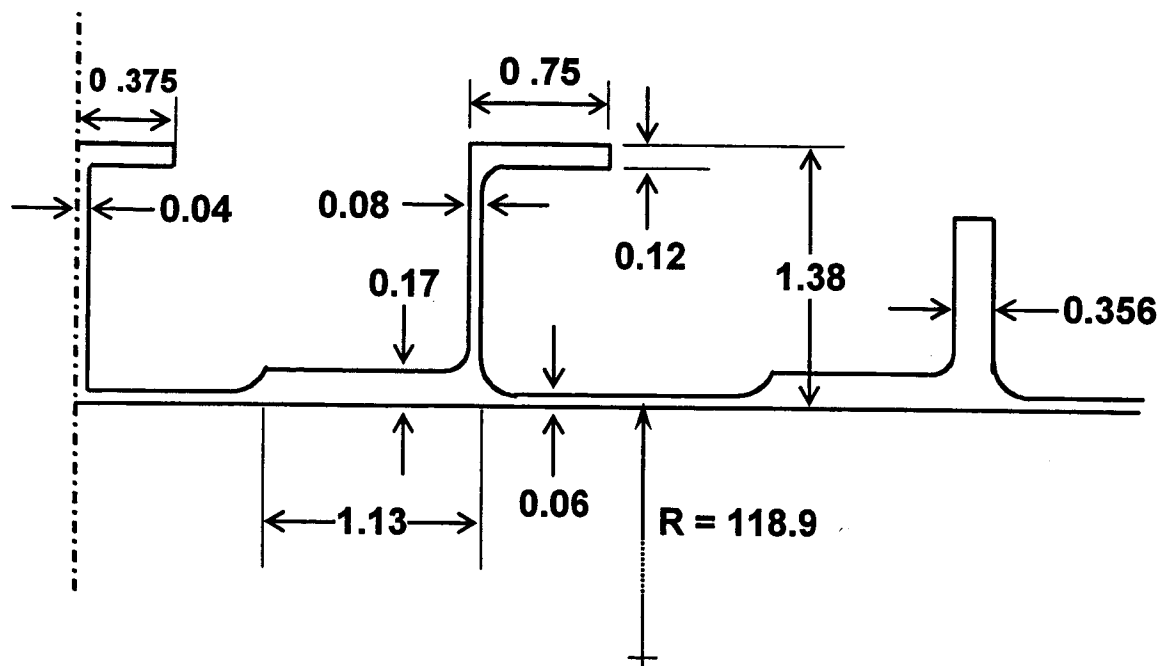
Fig. 3. Cross-sectional view of the curved integrally stiffened panel.
(All dimensions in inches)
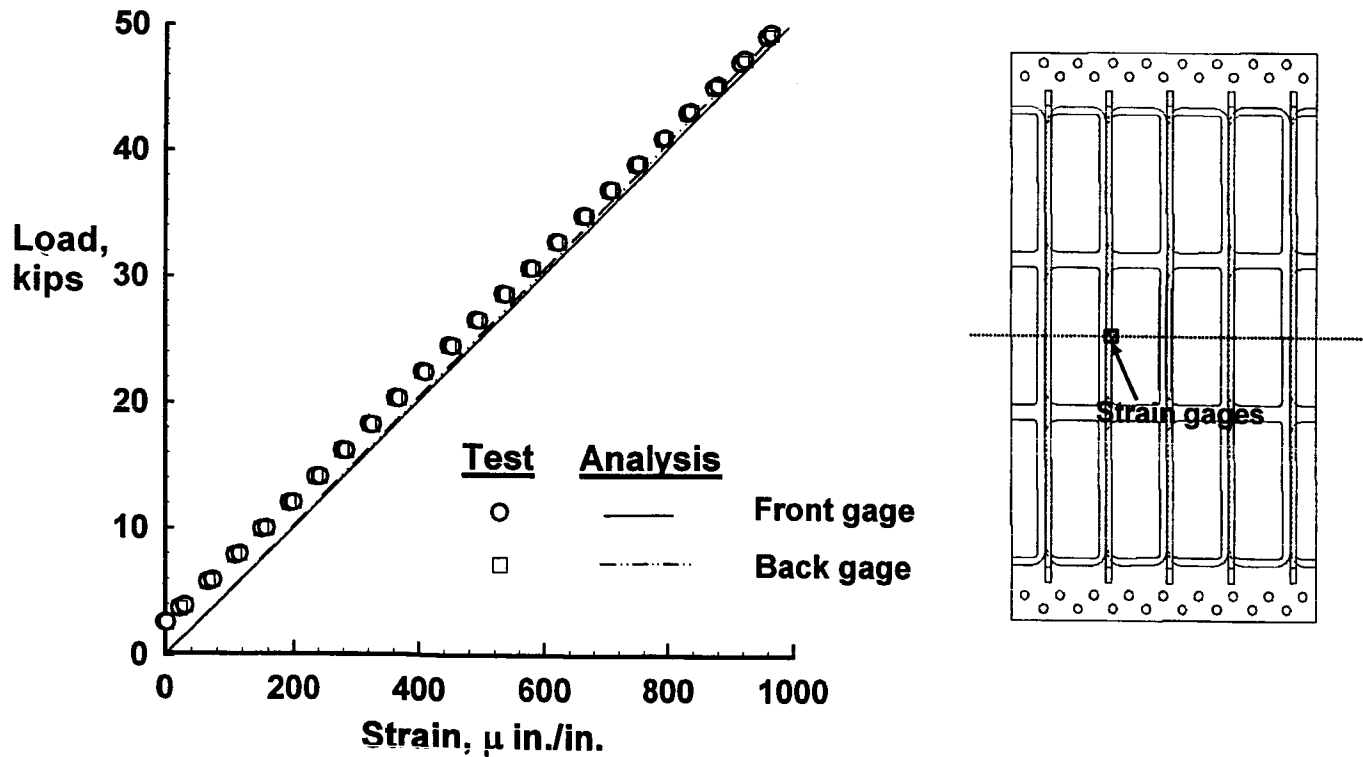
Fig. 4. Comparison of strain gage data on the curved sheet surface, preliminary test
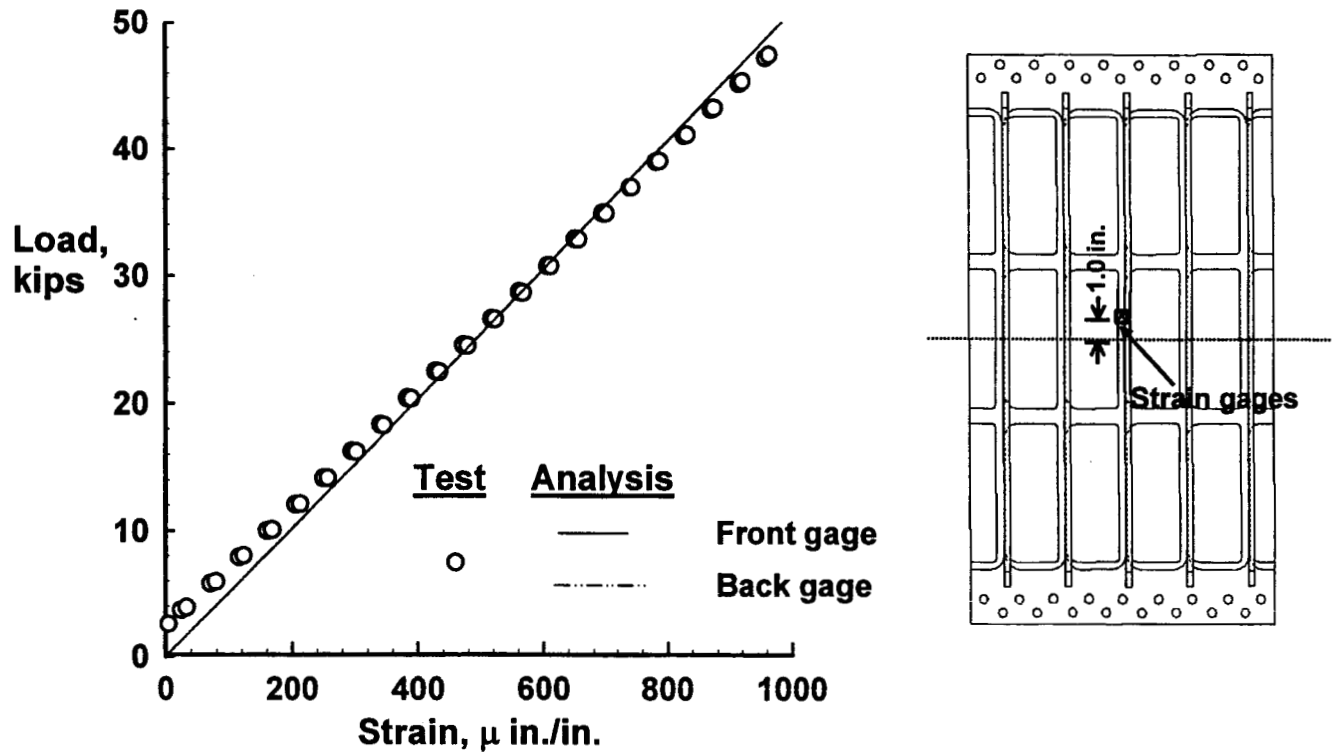
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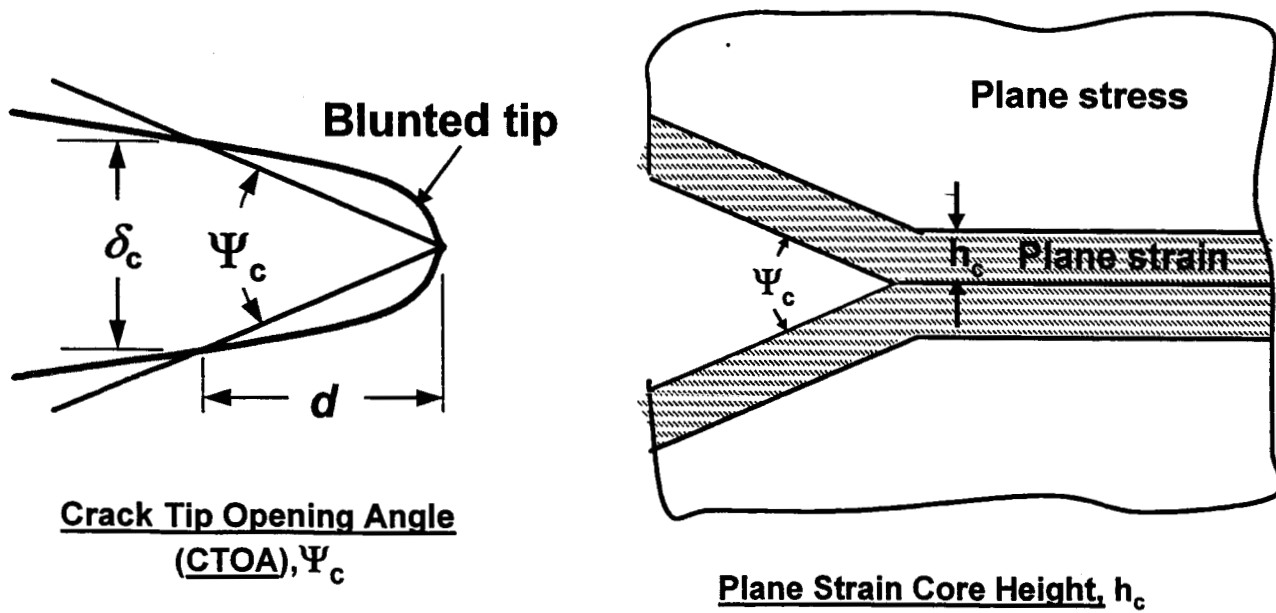
Fig. 6. Definition of fracture parameters
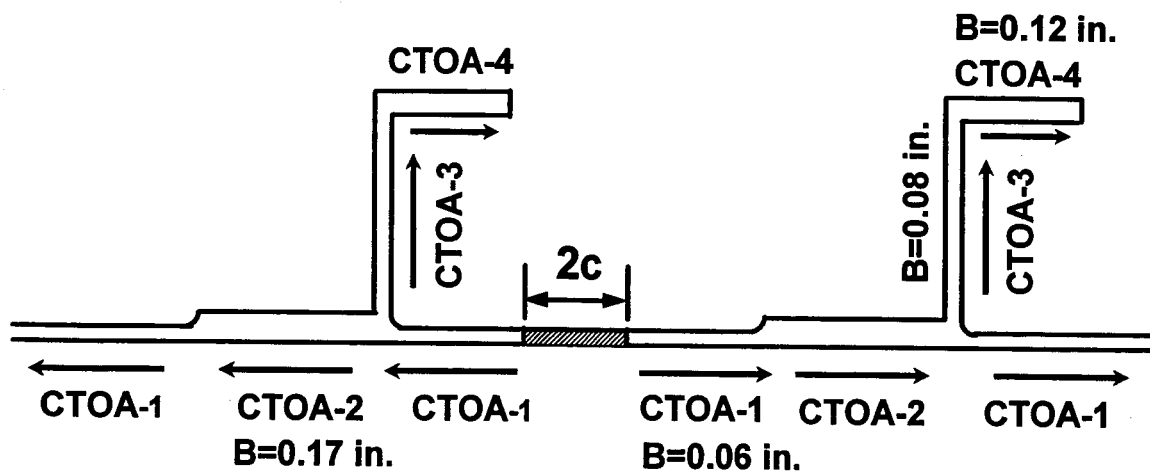
Fig. 7. Schematic representation of crack branching for 40-inch wide panel with CTOA criterion.
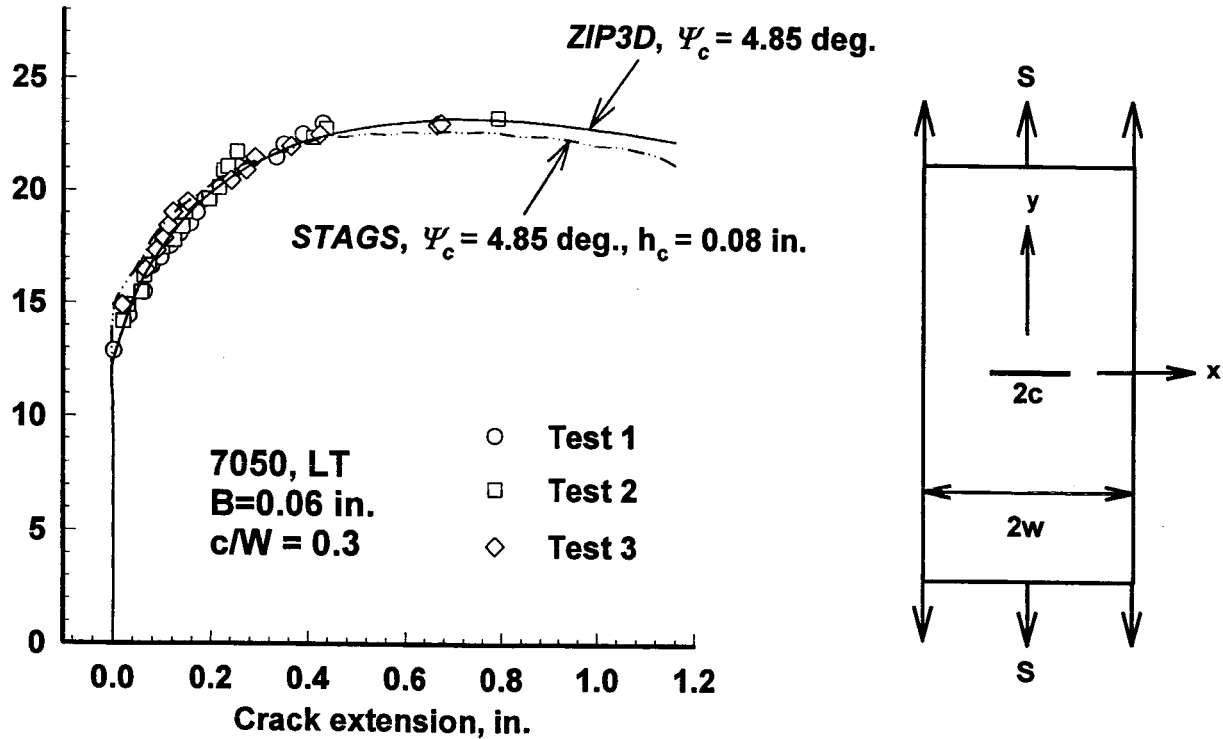
Fig. 8. Comparison of Load crack extension data for 12-inch wide M(T) specimen.
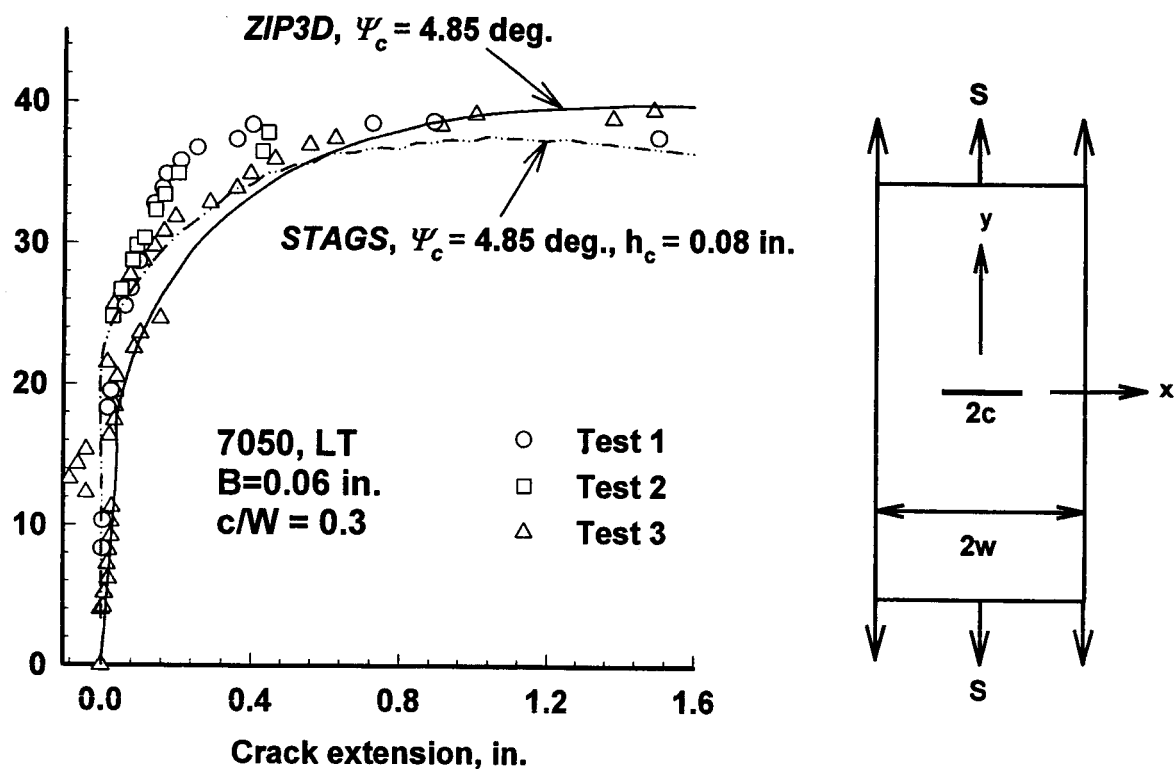
Fig. 9. Comparison of Load crack extension data for 24-inch wide M(T) specimen.
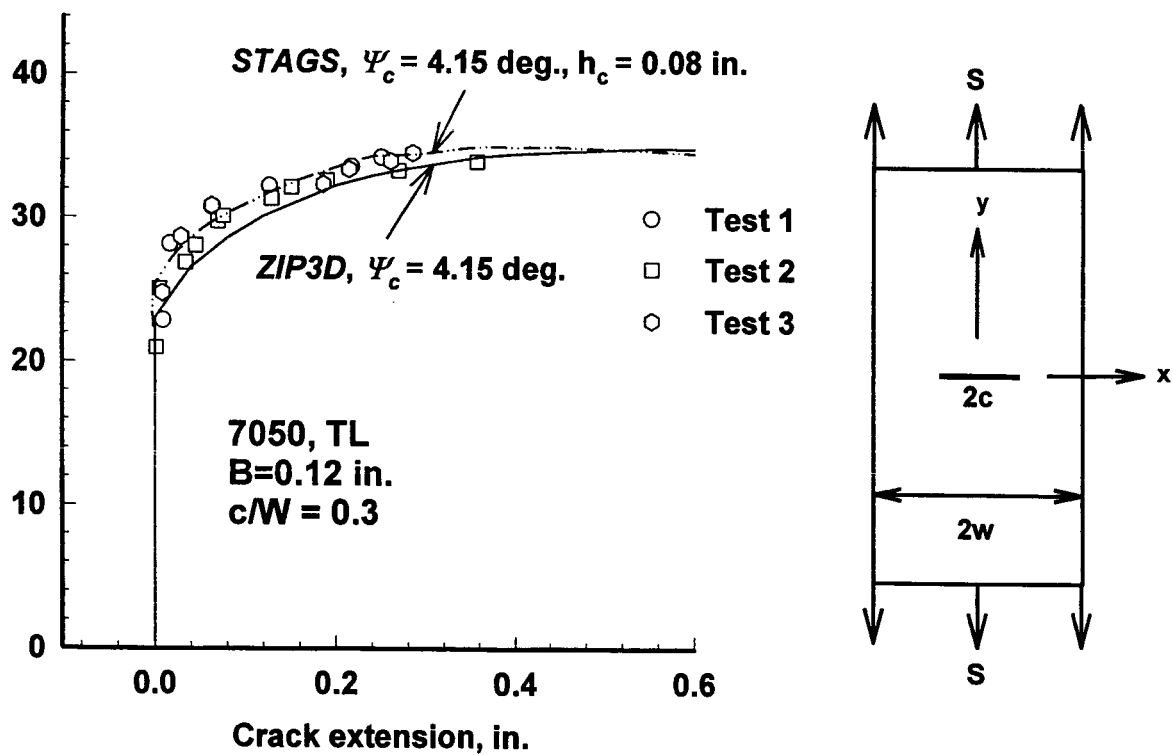
Fig. 10. Comparison of Load crack extension data for 12-inch wide TL, M(T) specimen.

Quarter model

Element type: 410 shell element
DOF per node: 6
Total number of nodes: 12,729
Total number of elements: 10,334
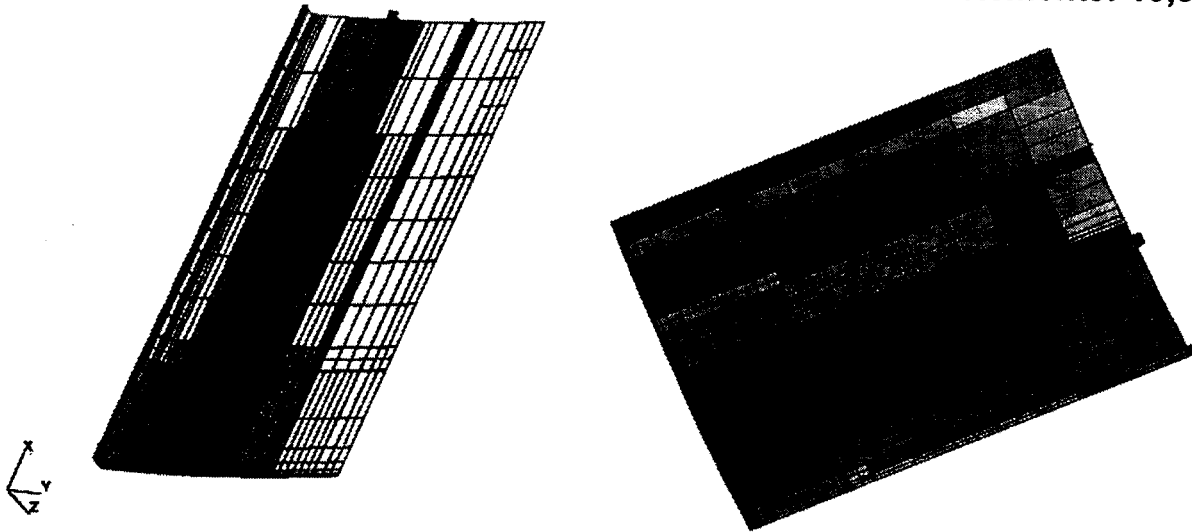
Fig. 11. A typical finite element model of a curved-integrally stiffened panel.

$\Psi_c = 4.85$ deg., da = 0.04 in.,
$h_c = 0.08$ in.

Panel failure

7050, W = 48.0 in.
$c_i / W = 0.145833$

Test

○ Right Crack tip
□ Left Crack Tip

Load, kips

Crack Extension, Δc, in.
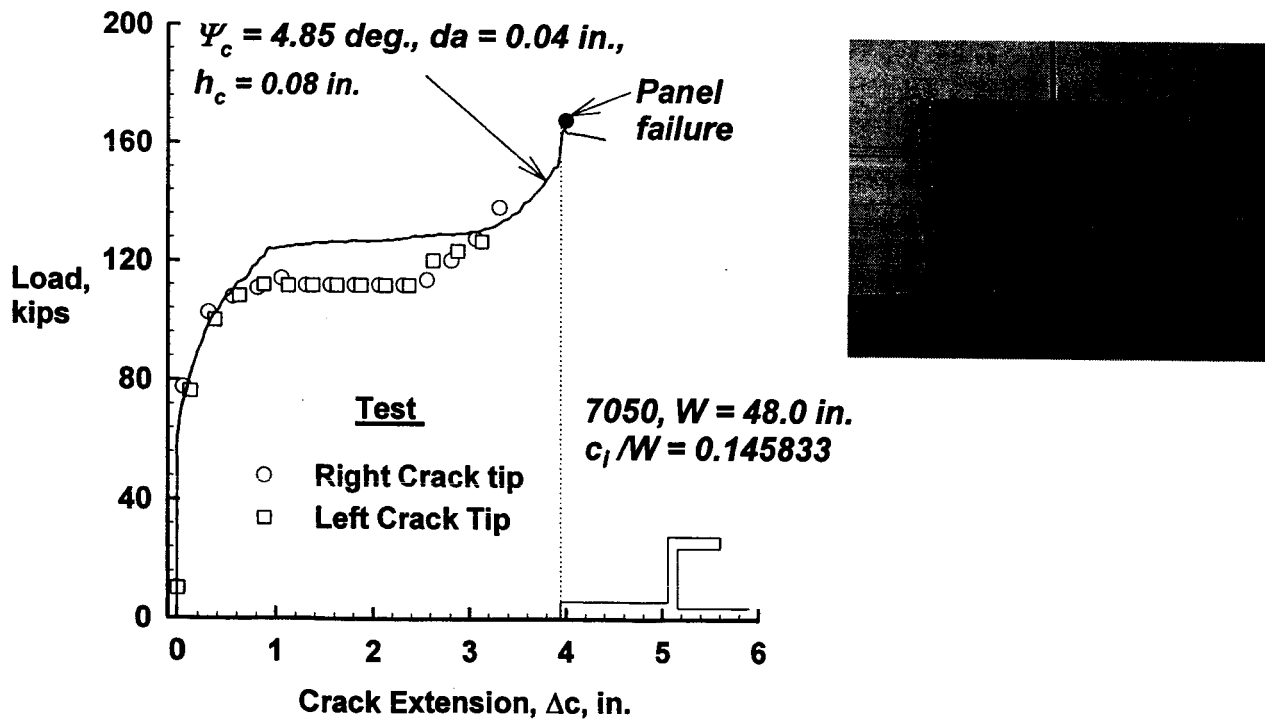
Fig. 12. Comparison of load-crack extension data for 48-inch wide curved integrally stiffened panel.
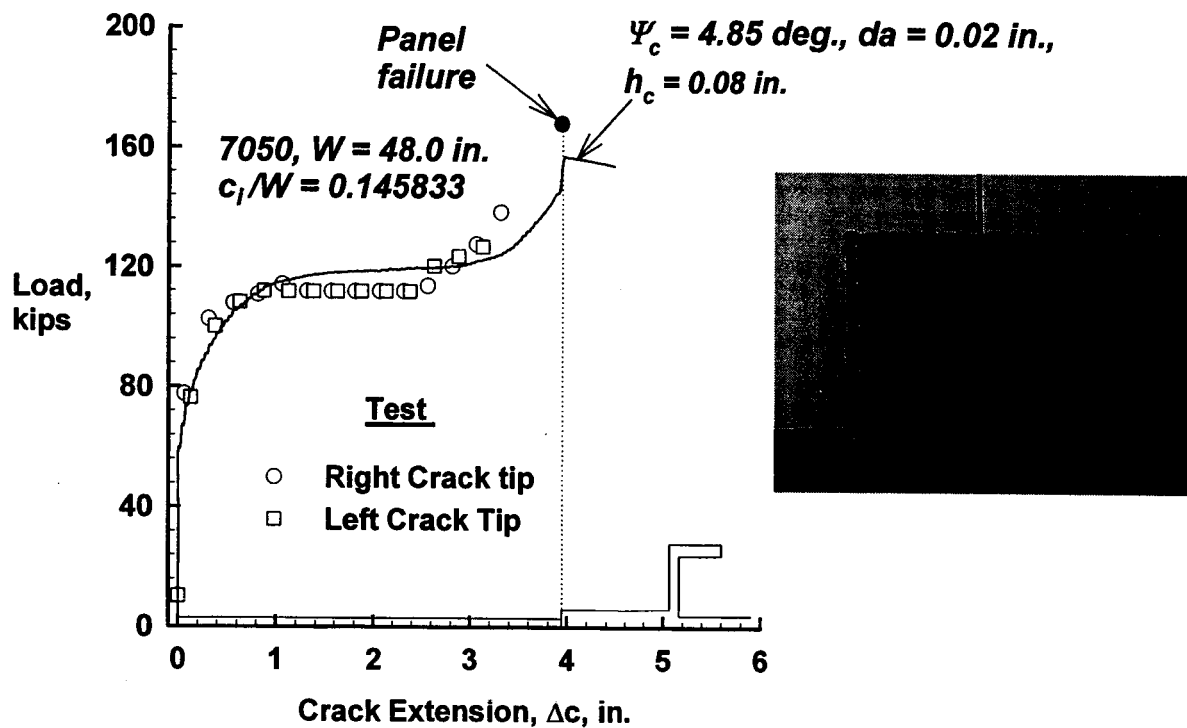
Fig. 13. Comparison of load-crack extension data with refined mesh for 48-inch wide curved integrally stiffened panel.
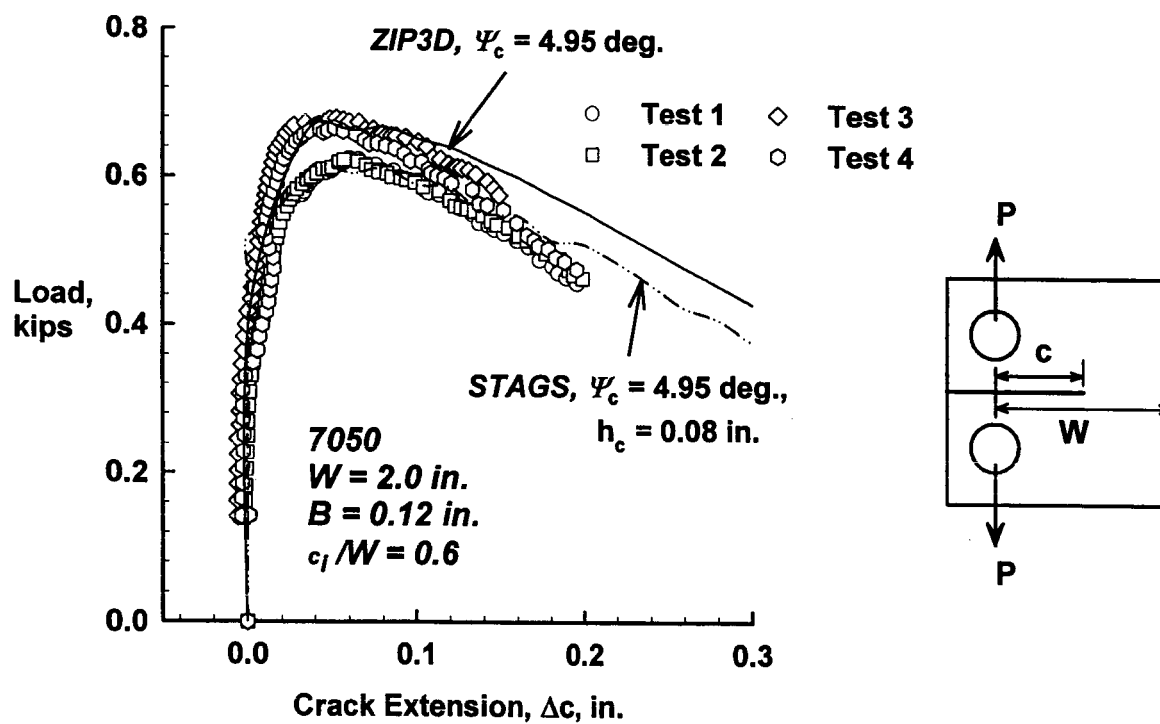

Fig. 14. Comparison of load-crack extension data for 2-inch wide, B=0.12 in., C(T) specimen.
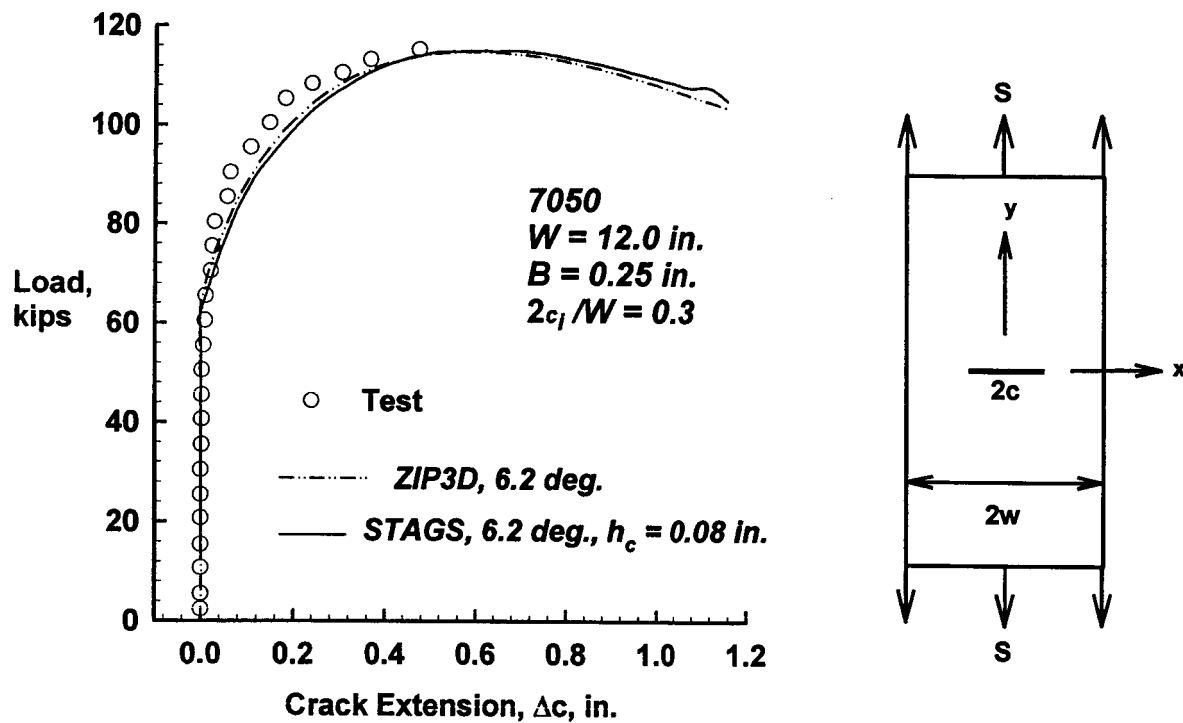
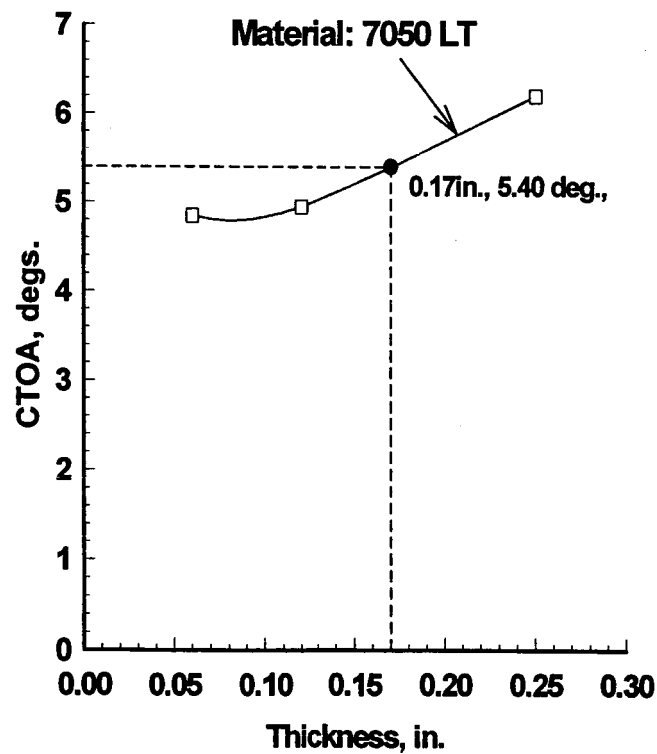Fig. 15. Comparison of load-crack extension data for 12-inch wide, B=0.25 in., M(T) specimen.

Fig. 16. Variation in CTOA as a function of thickness for 7050 LT material.
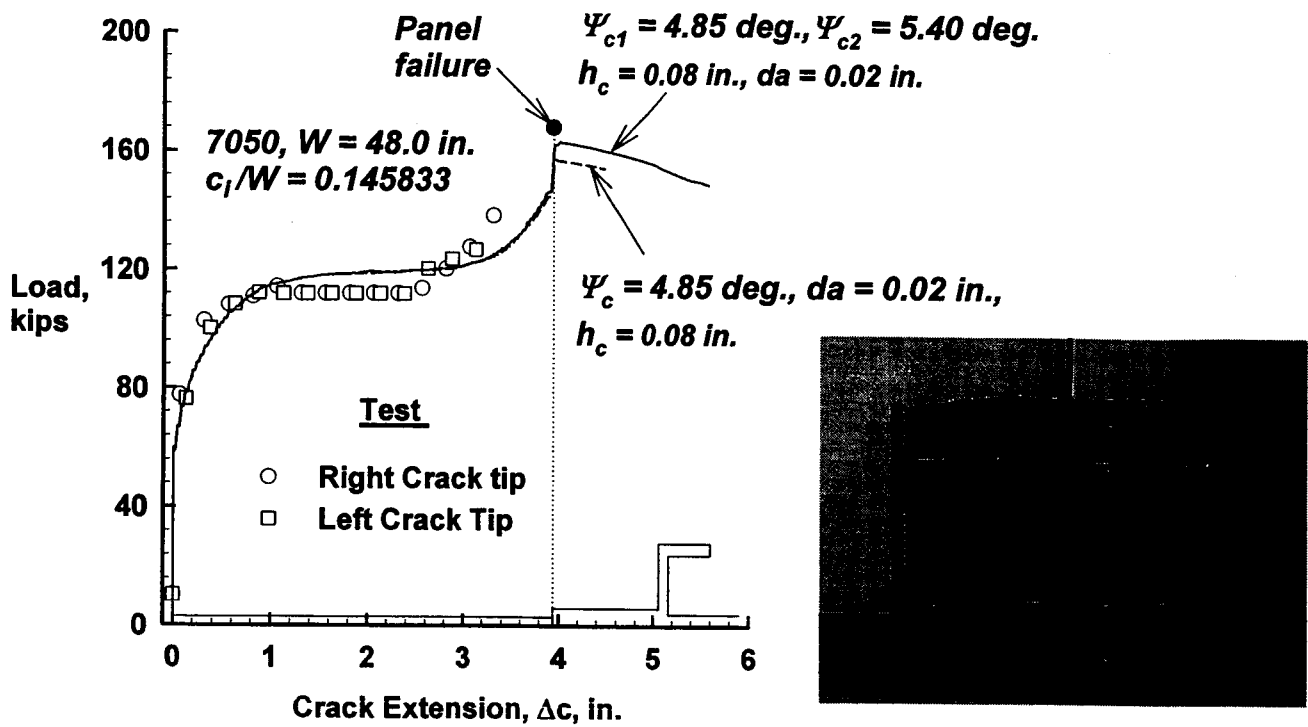
Fig. 17. Comparison of load-crack extension data with different CTOAs for 48-inch wide curved integrally stiffened panel.
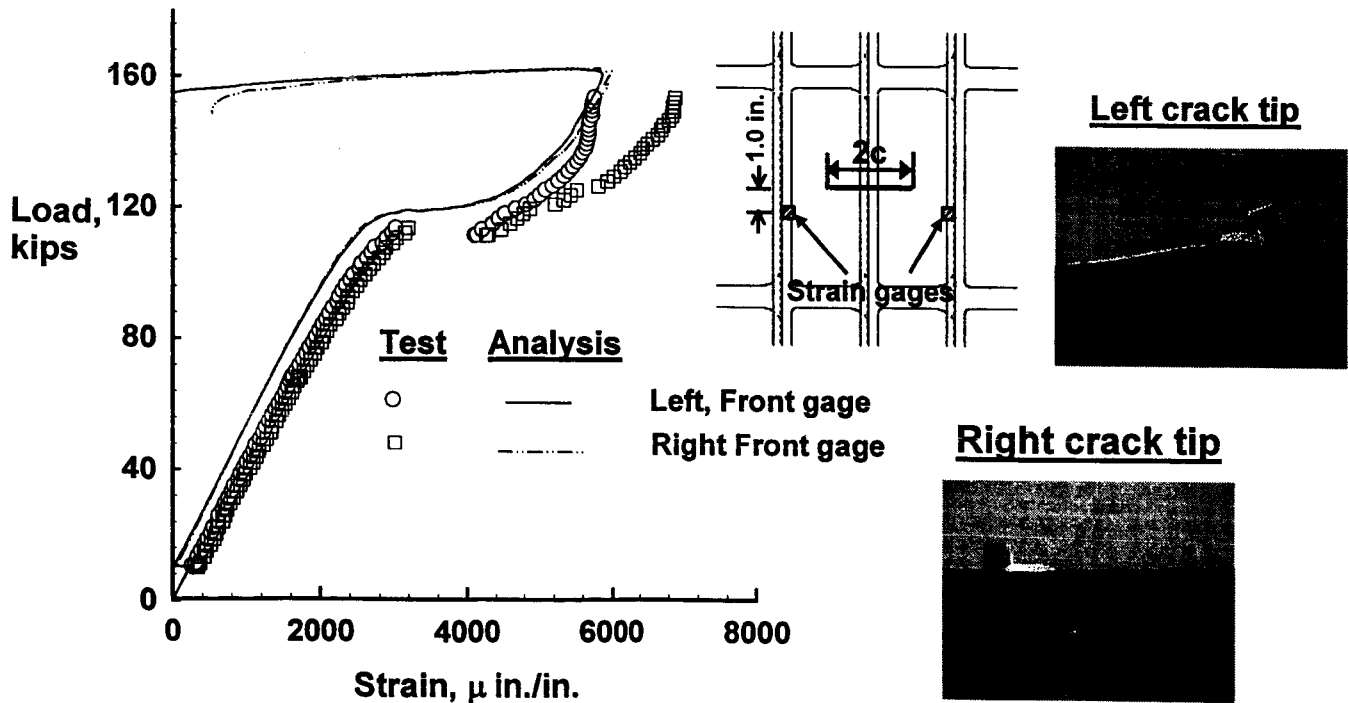

Fig. 18. Comparison of strain-gage data on the integral for 48-inch wide curved integrally stiffened panel, fracture test.